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Articles

Variation of surface runoff due to change of land use in the river Duero watershed

Variación de la escorrentía superficial por el cambio de uso de suelo en la cuenca del río Duero

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Abstract

The dynamics and availability of the water resource is fundamental aspect in the study of watersheds. From the temporal perspective, water

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resource is related to precipitation, which varies with hydrometeorological events, while spatially, it is largely related to the land use or vegetation cover. The changes in surface runoff of the Duero River basin, Mexico, using the SWAT model were investigated. The input data for the model include climatic variables, soil properties, topography, and four periods of land use map. The runoff estimates of the SWAT were compared with the streamflow data from the National Data Bank of Surface Water. An elevated record of runoff of up to 30 Dam^3 (cubic decameter) was observed in 1983 in the municipalities of Tangamandapio and Tangancicuaro, which was likely associated with forest clearing since the 1970s. A decrease of runoff to 10 Dam^3 was also observed in 2000, likely reflecting the conservation practice of forest management. The simulations for 2011 and 2014 indicate high runoff in the municipality of Chilchota due to the modification of its forest areas and traditional agriculture to accommodate the cultivation of the avocado crop and berries.

Keywords: SWAT model, artificial neural networks, digital mapping.

Resumen

La dinámica y disponibilidad del recurso hídrico es un aspecto fundamental en el estudio de las cuencas hidrográficas. Desde la perspectiva temporal, el recurso hídrico está relacionado con la precipitación, que varía con los eventos hidrometeorológicos, mientras que espacialmente, está relacionado en gran medida con el uso de la tierra o la cubierta vegetal. Se investigaron los cambios en la escorrentía superficial del río Duero basin, México, utilizando el modelo SWAT. The input data for the model include climatic variables, soil properties, topography, and four periods of land use map. Las estimaciones de escorrentía del SWAT se compararon con los datos de caudal del Banco Nacional de Datos de Aguas Superficiales. En 1983 se observó un registro elevado de escorrentía de hasta 30 Dam^3 (decámetro cúbico) en los municipios de Tangamandapio y Tangancícuaro, que probablemente se asoció con la tala de bosques desde la década de 1970; también se observó una disminución de escorrentía a 10 Dam^3 en 2000, lo que probablemente refleja la práctica de conservación del manejo forestal. Las simulaciones para 2011 y 2014 indican alta escorrentía en el municipio de Chilchota debido a la modificación de sus áreas forestales y agricultura tradicional para acomodar el cultivo del aguacate y bayas.

Palabras clave: Modelo SWAT, redes neuronales artificiales, mapeo digital.

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Introduction

Land-use change affects surface runoff dynamics, and the quantification of its effect is important for understanding the hydrological processes of river basins (Hundecha & Bárdossy, 2004). This change also alters climate processes at different scales and increases vulnerability to climate change (Cuo, 2016). One of the major land-use and land-cover changes is the conversion of forests over time, as a consequence of the agricultural activities and urban area expansion (Foley *et al*., 2005). In recent decades, studies have assessed the extent and condition of forest resources in the world and found that the main cause of deforestation comes from the need to obtain more arable land, with a strong tendency toward over-exploitation (FAO, 2001). Forest systems not only have a biological functionality but also regulate the export of nutrients, carbon storage, and their roots play an important role in providing resistance to soil erosion by reducing runoff velocity and binding the soil (Kauffman, Hughes, & Heider, 2009; DeFries, Rudel, Uriarte, & Hansen, 2010).

The Duero River basin in Mexico is facing serious environmental problems, such as water and soil pollution, overexploitation of groundwater, and changes in the use of soil and vegetation. Estrada-Godoy *et al*. (2013) reported the increasing vulnerability of the aquifer, which is mainly caused by overexploitation and the impact of agrochemicals used in the region. The chemical characteristics of ground and surface water resources have also been studied for different years and the results showed that groundwater has relatively good quality, while surface water is slightly or moderately contaminated (Silva et al., 2013). Silva-García et al. (2016) analyzed the operation, quality, and quantity of water from 49 springs, of which 27 are located upstream, in the municipality of Chilchota. Results showed that these springs have good chemical quality in general but are susceptible to punctual and diffuse pollution (wastewater, agricultural activities, recreational and urban growth). Cruz-Cárdenas, Silva, Ochoa-Estrada, Estrada-Godoy, and Nava-Velázquez (2017) defined environmental variable units using climate, topography, soil, and water properties and used remote sensing data to quantify urban growth. They classified five environmental units based on the water quality of the sampled wells and defined their uses: values from 0.75 to 2.25 μS cm-1 are suitable for irrigation under certain regulations, while values > 2.25 μS cm-1 are not recommended for some uses. The classified environmental units allow for the allocation of conservation areas and the use of resources.

Regarding natural resources evaluation, previous studies have focused on developing methodologies and tools that can be used to model the environment, such as digital mapping and hydrological modeling. The former evaluates and measures the change in land use and vegetation using remote sensing data and computer algorithms, which can be used to discriminate different land covers within a satellite image (Congalton, 1991; Cruz-Cárdenas et al., 2010). Meanwhile, hydrological models are simplified representations of the processes that occur in a basin. In this context, it is important to maintain a holistic view to characterize the dynamics of the model’s attributes and predict how processes will behave via simulation (Soetaert & Herman, 2008; Jiménez-Valverde, Acevedo, Barbosa, Lobo, & Real, 2013). Most hydrological models are based on the water balance equation to study cause and effect relationships, which allows to estimate the availability of water in a region under the principle of continuity, i.e., the models quantify inputs and outputs, as well as the changes in storage within the basin (Hernández, Scarpare, & Seabra, 2018).

Studies on hydrological modeling have been conducted in different parts of the world. These studies have analyzed the impact of changes in vegetation on the hydrological process in the basin(Zhou *et al*., 2013; Gebremicael, Mohamed, Betrie, Van-der-Zaag, & Teferi, 2013; Brouziyne, Abouabdillah, Bouabid, Benaabidate, & Oueslati, 2017). The development of hydrological models, such as the soil and water assessment tool (SWAT), has provided the capability to simulate hydrological processes (Xiong, Xu, Ren, Huang, & Huang, 2019), obtain estimates with acceptable precision (Nie *et al*., 2011; Baker & Miller, 2013; Ha, Bastiaanssen, Griensven, Van Dijk, & Senay, 2018), and facilitate decision making in terms of the adequate use of water resources (Jayakrishnan, Srinivasan, Santhi, & Arnold, 2005).

The SWAT model is a continuous dynamic model based on the mathematical descriptions of physical, bio-geochemical and hydrochemical processes and has been used for different hydrographic basins of Mexico and the world (Torres-Benites, Fernández-Reynoso, Oropeza-Mota, & Mejía-Saenz, 2004; Barrios & Urribarri, 2010; Arnold *et al*., 2012; Bautista-Ávalos, Cruz-Cárdenas, G., Moncayo-Estrada, Silva, &

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

Estrada-Godoy, 2014; Meng, Yu, & Liu, 2015). It is designed to evaluate the effect of topography, soils, land use, and climate on the hydrologic response of ungauged basins, the data used to generate the input parameters may be scarce or absent (Srinivasan, Zhang, & Arnold, 2010). Depending on the complexity of the study and the data available, this model defines the hydrologic response units (HRUs) to show differences in transpiration and other hydrological conditions for the diverse soil characteristics of land use and vegetation (Neitsch, Arnold, Kiniry, Srinivasan, & Williams, 2010).

Because there is a conversion of vegetation by human activities in the Duero River basin, the main aim of this study was to evaluate the variation of surface runoff in four scenarios of change in land use and vegetation (1983, 2000, 2011, and 2014) with the SWAT model.

Materials and methods

Study area

The Duero River basin is located on the northwest of the state of Michoacán (19°40'- 20°15'N, 101°45' -102°45' W). It covers an area of 2531.3 km^2 with an elevation range from 1500 to 2400 m (Figure 1). The area is characterized by a subhumid climate ((A) C (wo), C (w1), and C (w2)). The basin is a predominantly volcanic environment with stratovolcano structures (Silva & Ramos, 1998). Vertisol is the dominant agricultural soil type in the valleys to produce vegetables, basic grains, and berries and it covers over 50 % of the basin area, meanwhile, the Andosol soil located in the mountains is used for avocado production (Estrada-Godoy *et al*., 2013).

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

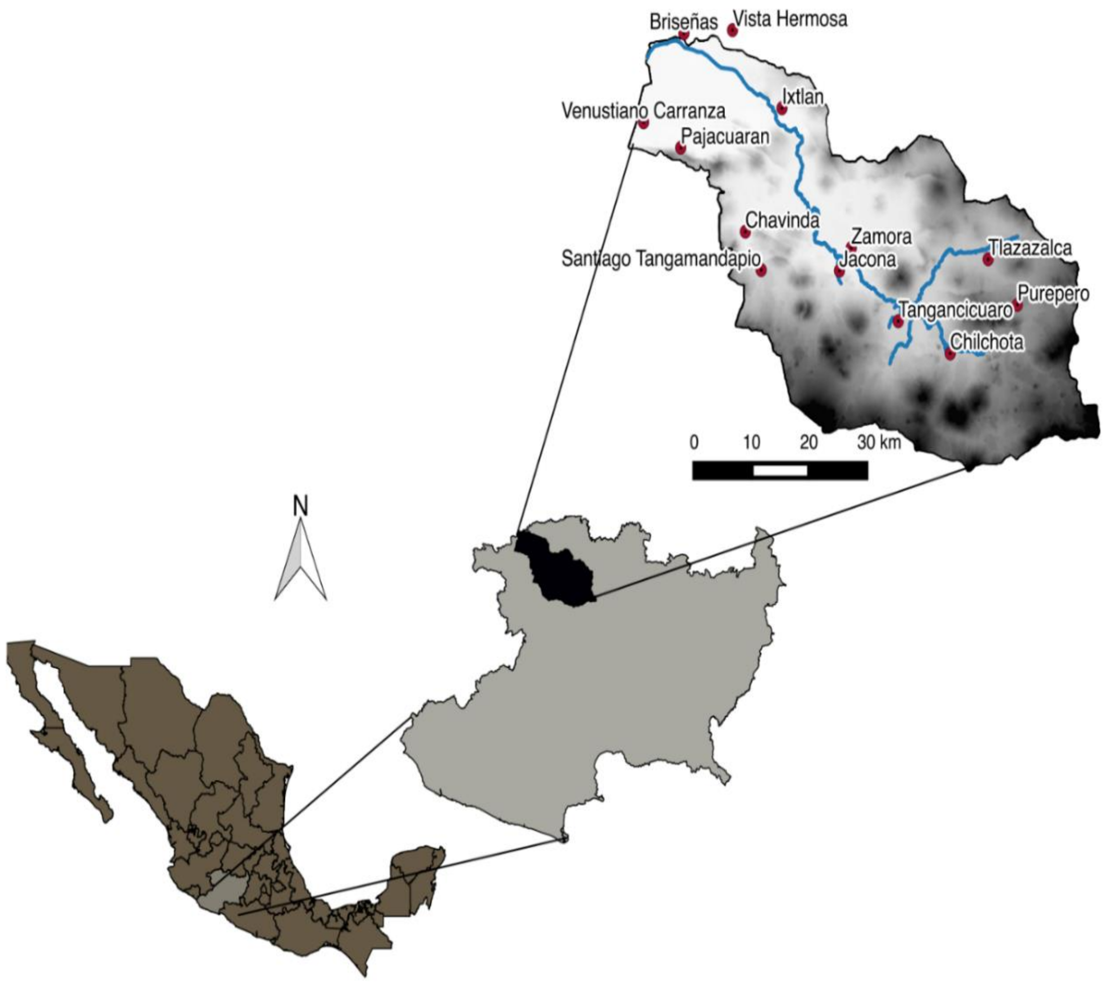

Figure 1. Location of the Duero River basin, Michoacán, Mexico.

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

Topographic attributes

The digital elevation model (DEM) of the basin was obtained from the Mexican Territory Elevations Model (INEGI, 2014), with a pixel resolution of 30 m x 30 m. This dataset was used to generate areas of three slope intervals: < 5 %, between 5 and 10 %, and > 10 % (Neitsch *et al*., 2010).

Climate data

Fourteen climate variables were used to feed the SWAT model (Neitsch *et al*., 2010). The meteorological information was obtained from the Rapid Extractor of Weather Information (ERIC III version 2.0 of the Mexican Institute of Water Technology). A filter was applied to select stations that were at least 20 years old and had data with >80 % of the available records per year. In the end, 20 meteorological stations within the basin were selected. The solar radiation, dew point, and wind speed variables were calculated based on the data provided by 10 nodes of the National Center for Environmental Prediction (NCEP, 2014). The mean annual temperature and accumulated precipitation were obtained from the whole

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

database from the selected meteorological stations.

Soil Properties

The soil profiles were described from six sites chosen based on the soil units map of INIFAP and Conabio (1995). Soil samples were collected and analyzed from each soil layer according to the Official Mexican Standard NOM-021-RECNAT-2000 (Semarnat, 2002). The soil properties required for the model are depth, apparent density, saturated hydraulic conductivity, soil erosion, organic carbon content, rock fragment content, electrical conductivity, available water capacity, and percentage of sand, silt, and clay.

Land use

Digital mapping technique was used to obtain and quantify different types of land use in the Duero River basin. This is the recommended method

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

when the area is known because it allows the selection of the classes to be analyzed (Chuvieco, 2002). The remote sensing data used include Landsat 5, Landsat 7, and Landsat 8 satellite images for four periods (1983, 2000, 2011, and 2014) with a spatial resolution of 30 x 30 m. The DEM was also used in the digital mapping process to improve the accuracy of the maps (Cruz-Cárdenas *et al*., 2010).

A total of 250 sampling points were categorized into the following classes of land use: agriculture (A), pine-oak forest (POF), grassland (G), shrub (M), and urban area (UA). Seventy percent of the sampling sites were randomly selected to perform the automated mapping using five algorithms: artificial neural networks (ANN), decision trees (CTA), minimum distance (DM), maximum likelihood (ML), and parallelepiped (PP) (Lo & Yeung, 2007). After the classification, the remaining 30 % of the points were used to validate the land use and vegetation maps. A confusion matrix was generated to measure the reliability of the maps using the overall accuracy and the kappa coefficient (Congalton, 1991).

Calibration and validation of the SWAT model

The SWAT model divides the basin into sub-basins based on the digital

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

elevation model. A flow accumulation layer will be generated from one layer of flow direction. A flow network is created, and the main channel is divided and ordered into continuous segments. The accumulation points of each network are calculated, and the delimitation of sub-basins is carried out. Then, these sub-basins are divided into hydrologic response units (HRUs) according to the topography, land use, and soil type. Finally, with the SWAT input files (Arnold *et al*., 2012), the simulation, calibration, and validation of the model are implemented (Figure 2).

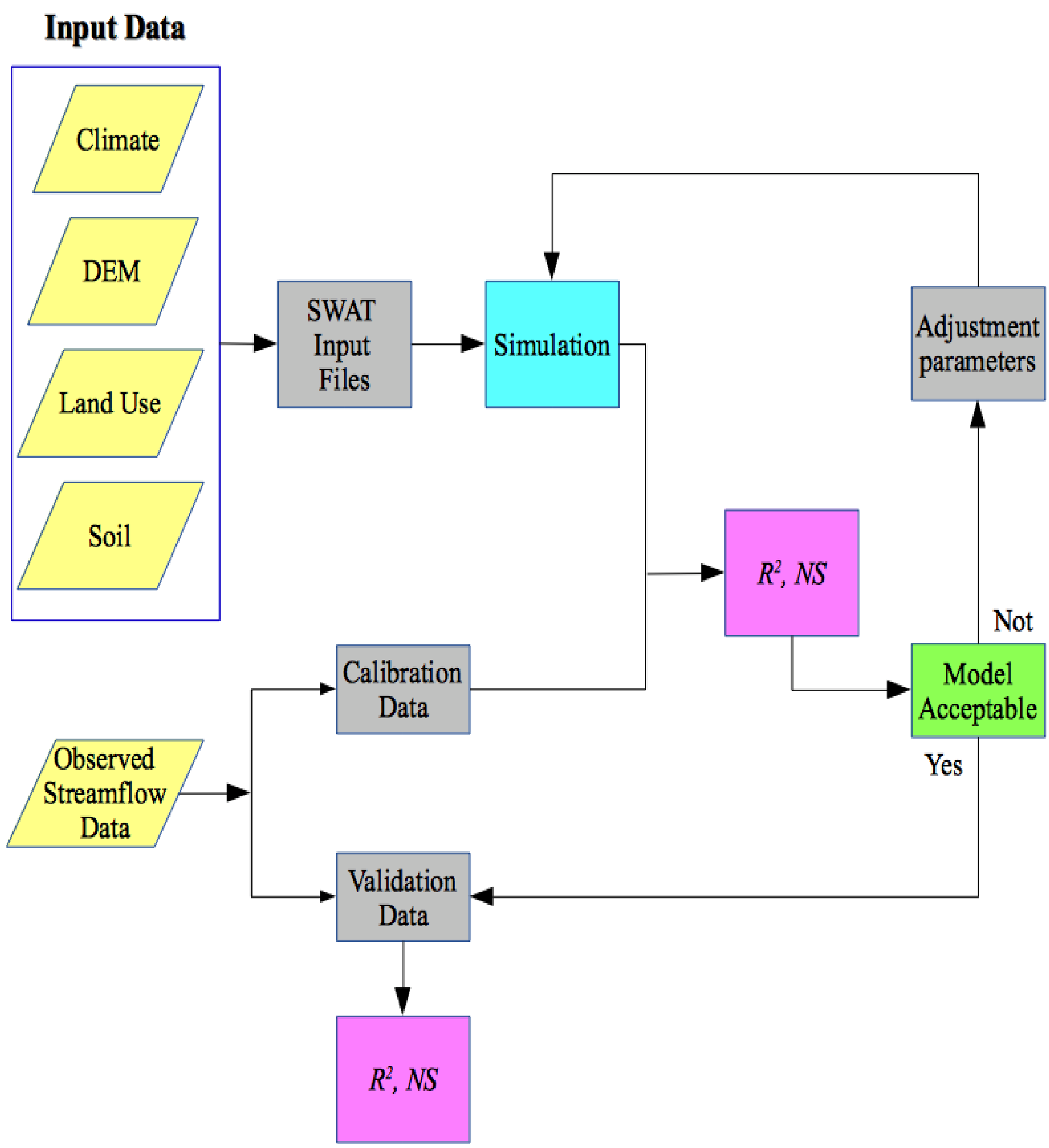

Figure 2. Flowchart of the model construction, calibration, and validation processes. DEM = digital elevation model; R^2 = coefficient of determination; NS = Nash-Sutcliffe efficiency.

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

The calibration and validation processes were performed using a partition of the observed data available. The calibration was configured manually, adjusting the values of the curve number parameter (NC2) (Boyle, Gupta, & Sorooshian, 2000; Arnold *et al*., 2012). The streamflow records (in m^3 s^{-1}) of the hydrological stations' network from the National Bank of Surface Water (NBSW) were used for model calibration and validation. Twenty-one hydrological stations are in the basin, however, six were selected because they have records from 20 years (1980-2000).

The calibration of the 1983 land-use scenario was done using the monthly average streamflow from 1980-1982, and the validation with the streamflow from 1983-1984. In the 2000 land-use scenario, the streamflow from 1995 to 1997 was used for calibration, meanwhile, the streamflow from 1998 to 1999 was used for validation. In both scenarios, the SWAT-estimated runoff was compared to the observed streamflow (NBSW). The Nash-Sutcliffe efficiency (NS) (Nash & Sutcliffe, 1970) and the coefficient of determination (R^2) (Krause, Boyle, & Bäse, 2005) were calculated to measure the goodness of fit. These coefficients were chosen as suitable methods for judging the goodness of fit of a hydrological model (Nash & Sutcliffe, 1970).

Results

The analysis of the temperature and precipitation data from the 20 meteorological stations showed that both variables changed in the Duero River basin (Figure 3). Particularly, the mean annual temperature showed an increase of 0.8 °C, and the precipitation decreased by 90 mm over 60 years.

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

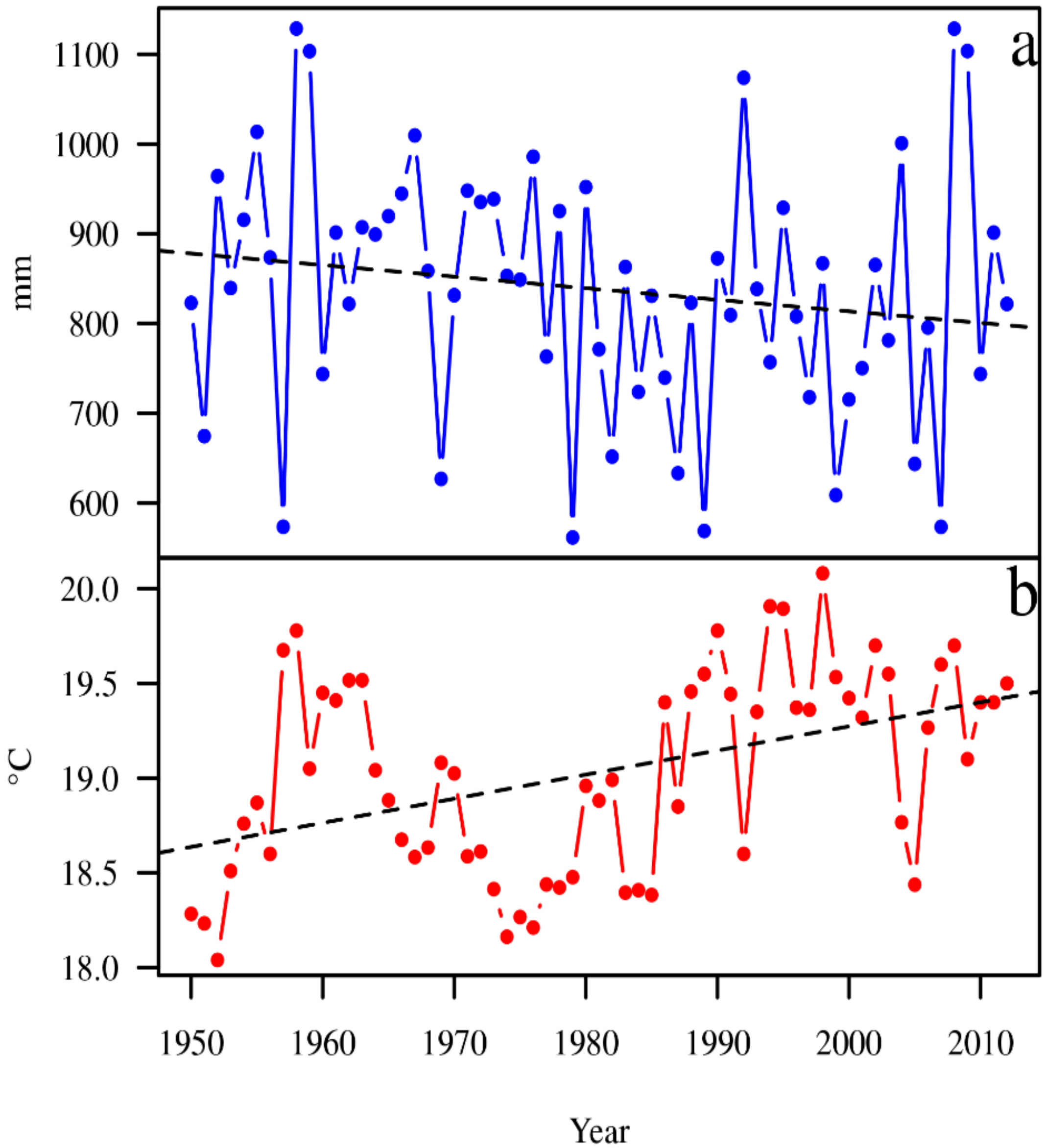

Figure 3. Climatic variables of the Duero River basin (60 years): a) Annual precipitation; b) annual average temperature.

The five algorithms used for the digital mapping yielded a more than 60 % agreement between classified classes and validated data. Among these methods, both ANN and ML reach the classification accuracy of >80 %. Based on the expert knowledge of the study area, we considered that the maps generated by the ANN method better represented the distribution of land use (Figure 4).

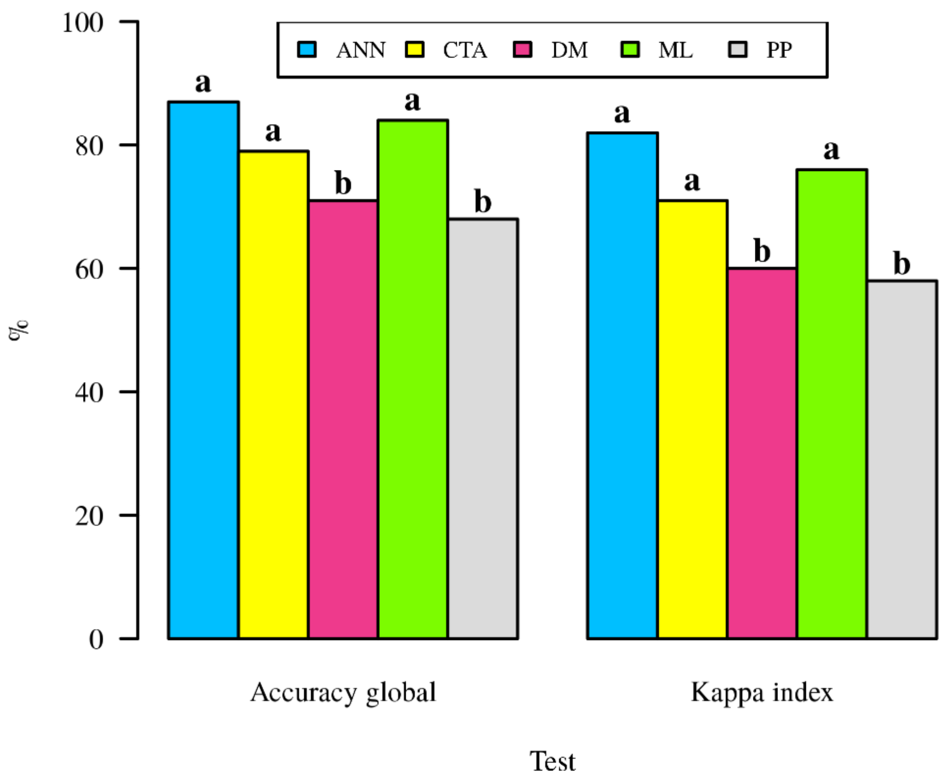

Figure 4. Mean comparison (p-value = 0.05; different letters represent a significant difference), with global accuracy and kappa index, of five classifiers for digital mapping. ANN = artificial neural networks; CTA =

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

decision trees; DM = minimum distance; ML = maximum likelihood; PP = parallelepiped. The best algorithms for the classification were neural networks and maximum likelihood, with concordance values above 84 and 89 %, respectively, in the classification of pixels.

The distributions of the five classes of land use from 1983 to 2014 are shown in Figure 5. From 1983 to 2000, land covers of G, S, and UA increased 15.5, 8.8, and 0.3 %, respectively. In contrast, land use of A and POF showed losses of 15.2 and 9.3 %, respectively. This period presented the greatest loss of pine-oak forest over the 17 years. From 2000 to 2011, the land covers with positive rates were A (3.1 %), POF (2.4 %) and UA (0.4 %), while S (2.2 %) and G (3.8 %) had losses. From 2011 to 2014, the land covers with a positive rate corresponded to A (0.2 %), G (2.6 %) and UA (0.3 %), while POF (2.4 %) and S (0.7 %) had negative rates.

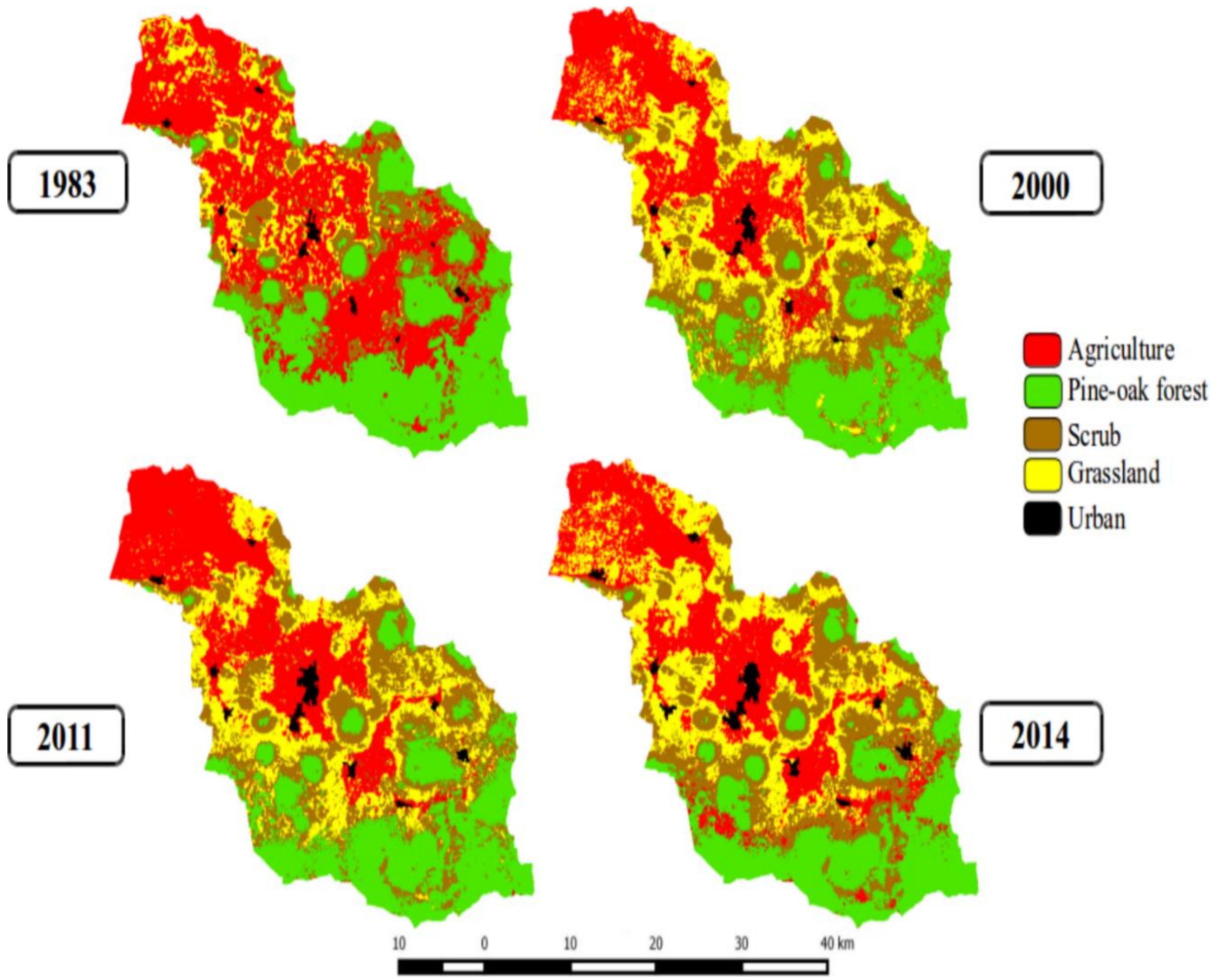

Figure 5. Land use for four scenarios for the Duero River basin. Maps generated using artificial neural networks were used.

In the SWAT model, the basin was divided into 25 sub-basins and at least 132 HRUs. No changes were made to the input parameters of the first simulation model for the land-use scenario of 1983.

Figure 6a shows a comparison between the observed and simulated streamflow that represents a clear difference between these two values. Although a high coefficient of determination was obtained (0.93) (Table 1), the Nash-Sutcliffe coefficient (NS) is only -2.24, indicating a poor predictive capacity of the model and that an adjustment is necessary. The three-year streamflow records (1980-1982) were used to calibrate the model, and a manual adjustment was done using the curve number values. Table 1 shows the summary of the calibration and validation models. In the calibration, a coefficient of determination of R^2 = 0.92 and a NSE of 0.51 imply that the model was still poor. For the validation, two-year data (1983-1984) were used, with R^2 = 0.96 and NSE = 0.61.

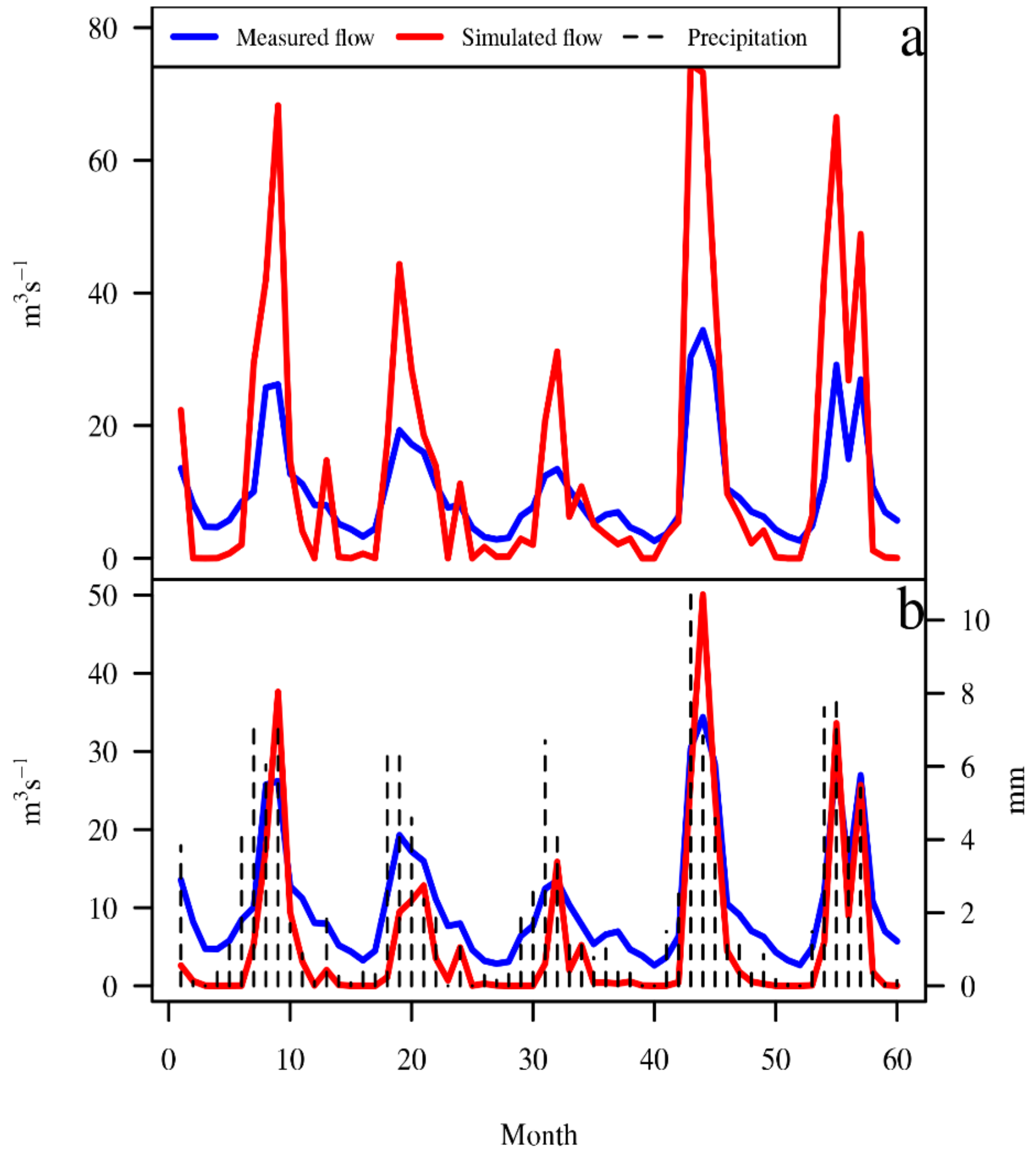

Figure 6. Comparison of observed and calculated monthly surface flow for the Duero River basin for the period from 1980-1984. a) First simulation; b) calibration (1-36 month) and validation (37-60 month). Additionally, the precipitation values are shown.

After the model was calibrated and validated, the observed and measured streamflow values were adjusted (Figure 6b). The peaks in the precipitation values indicate the wet months of each period.

Table 1. Summary of the calibration and simulation of the estimated and observed values of the runoff.

	Scenario 1983		**Scenario 2000**	
	R^2	NS	R^2	NS
First simulation	0.93	-2.24	0.96	-2.50
Calibration	0.92	0.51	0.94	0.54
Validation	0.96	0.61	0.91	0.70

R^2 = coefficient of determination; NS = Nash-Sutcliffe efficiency.

In the first simulation for the 2000 land-use scenario, the R^2 was 0.96 and the NS was -2.50 (Table 1). The calibration stage with data from 1995-1997 presented an R^2 of 0.94 and NS of 0.54 (Table 1). The validation for 1998-1999 presented an R^2 of 0.91 and NS of 0.70 (Table 1). When compared the streamflow this period also showed a better adjustment than in the first simulation (Figure 7).

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

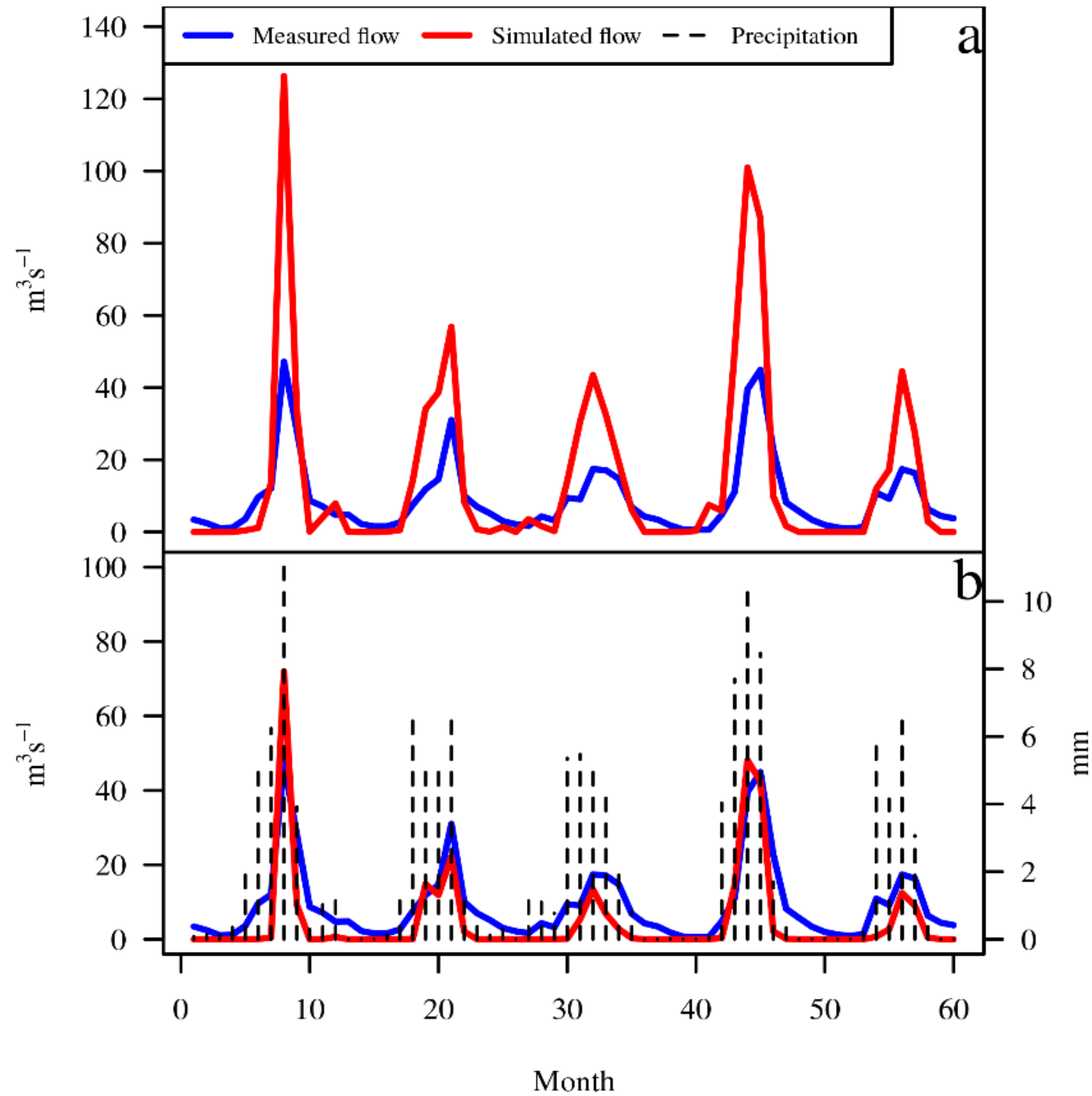

Figure 7. Comparison of observed and calculated surface flow for the Duero River basin for the period from 1995-1999. a) First simulation; b) calibration (1-36 month) and validation (37-60 month). Additionally, precipitation values are shown.

The initial NC2 values for both periods were 87, and the endpoints

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

were 73 for 1983 and 62 for 2000. In the case of the 2011 and 2014 periods, only the runoff was projected because of the lack of streamflow data available to perform the calibration and validation of the models.

Figure 8 shows the amount of surface runoff for each period. In the 1983 scenario 76 % of subbasins had runoff of less than 10 Dam^3 (cubic decameter) of water, while for 2000, this increased to 84 %, aspect that continued in the following scenarios. It was noted that in 1983 the subbasin number 16 had runoffs of approximately 30 Dam^3 of water, but in 2000, the same subbasin reduced its runoff to less than 10 Dam^3. In the 2011 and 2014 scenarios, the maximum runoff occurred in the highlands of the basin.

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

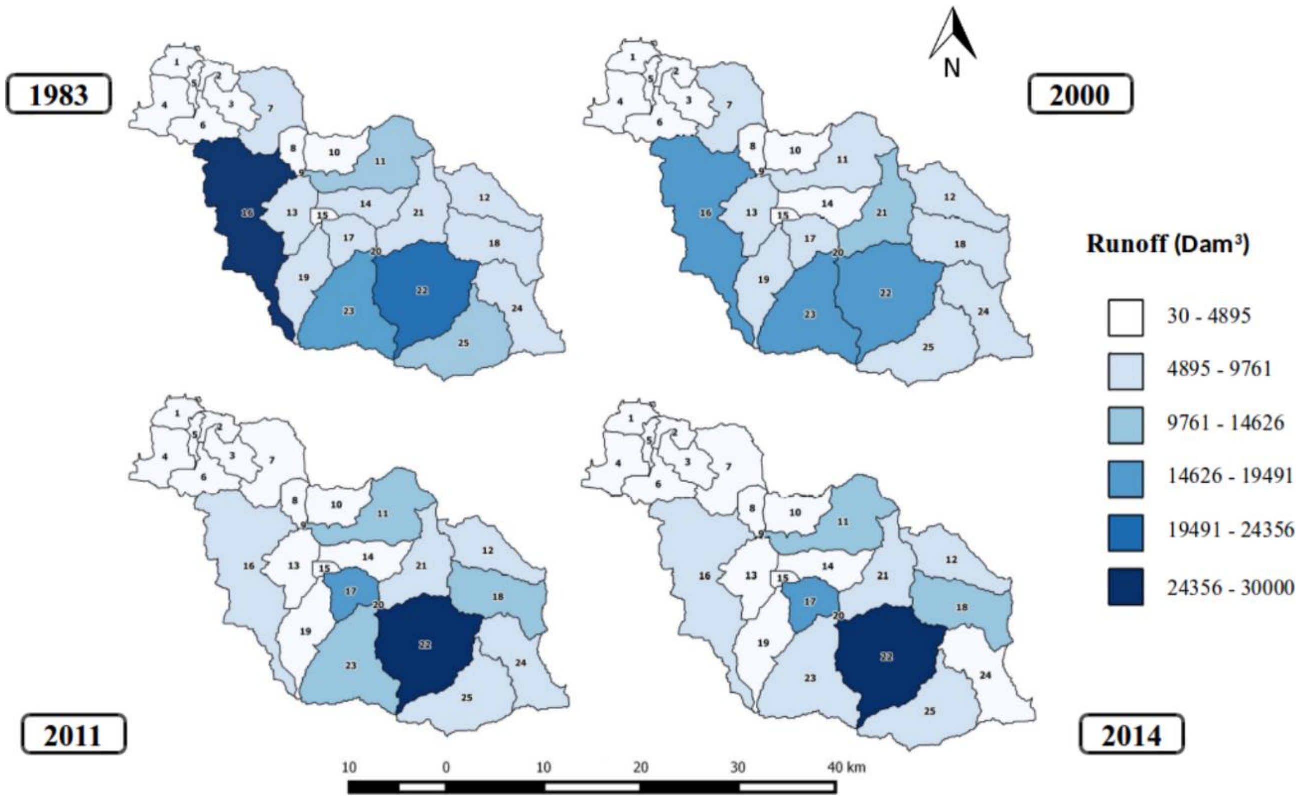

Figure 8. Surface runoff in the Duero River basin during different periods. Dam^3 = cubic decameter.

Discussion

The Intergovernmental Panel on Climate Change (IPCC) has projected annual average temperature changes under different scenarios of greenhouse gas emissions and concentrations, with a probable increase range of 0.3 °C to 0.7 °C (IPCC, 2014). In the Duero River basin, according to the projected values, there was an increase of 0.8 °C in the period from 1950 to 2010, which, at the regional level, could be attributed to the change in land use due to different anthropogenic activities (Magaña, 2004). The aforementioned factors influence the climate, which determines the adaptation of living organisms and a variety of climatic zones with different temperature, humidity, luminosity, and precipitation characteristics, being conducive to the natural selection of species (Valladares *et al*., 2014).

The land use maps presented high accuracy because the kappa values were between 0.73 to 0.84. According to Castillejo-González *et al*. (2009), and accuracy between 82 to 89 % for the map classification is acceptable. With both measurements of the goodness of fit, it is possible to confirm that within the remote sensing data, the defined classes were discriminated.

Bravo, Mendoza, and Medina (2009) mentioned that between the 1960s and 1980s, deforestation in the state of Michoacán was intensified. Mas-Caussel, Velásquez-Montes, and Fernández-Vargas (2005) reported that between 1976 and 2000, there was a conversion of 8500 ha of temperate forests to avocado plantations per year. This is because there are agroclimatic conditions in the Duero River basin for the establishment of avocado orchards, promoting a decrease in pine-oak forests (Fregoso, Velázquez, Bocco, & Cortéz, 2001). The expansion of this crop has led to deforestation processes, which, as in other basins with similar

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

characteristics, have had negative effects such as soil degradation, aquifer reduction, biodiversity loss, and plague emergence (Pineda-Jaimes, Bosque-Sendra, Gómez-Delgado, & Plata-Rocha, 2009). The deforestation process impacts at all scales: locally, with changes in the microclimate and detriment of the biodiversity; regionally, it affects the functioning of hydrographic basins; and at the global level, it contributes to emissions of greenhouse gases (Bocco, Mendoza, & Masera, 2001; Tölle, Engler, & Panitz, 2017). These changes can strongly degrade natural resources and increase the vulnerability of adjacent populations (DeFries *et al*., 2010; Gauquelin *et al*., 2018).

The first notable streamflow simulation differences between observed and simulated values promoted the implementation of a sensitivity analysis. Ma *et al*. (2000) recommended identifying the key and precision parameters to achieve a good calibration; therefore, a better parameterization of the model under local conditions and the consequent reduction of the prediction uncertainty can be achieved. The value of the selected parameter was chosen to be within its respective ranges of uncertainty to avoid overestimating or underestimating the outputs of the model. The SWAT model creates parameter tables related to the hydrological processes of the basin; the runoff curve number is one of the most sensitive parameters that affect the values of drained volumes (Arnold *et al*., 2012). The NC2 values of the Soil Conservation Service are assigned according to the soil type and vegetation cover with a variation of ± 10 %, which is an acceptable range of error. Arnold *et al*. (2012) indicated that adjusting the parameters by ± 10 % is an acceptable

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

practice for the values estimated by the SWAT model compared with those observed. The NC2 values of the models of the present study were 73 and 62 for the years 1983 and 2000, respectively. These values are within the ranges reported for each land use and vegetation. The values obtained for each land use and vegetation used in the basin were within their respective ranges.

The values obtained in the validation stage indicated that the models are very good according to the scale proposed by Nash and Sutcliffe (1970), while the R^2 values can be considered good only when they are from 0.7 to 0.9, (i.e., close to 1), providing an estimation based on the observed values replicated by the model (Krause *et al*., 2005).

According to Choi (2007), anthropic alterations to a vegetal cover increase drained volumes because the runoff coefficient is related to the texture and land use. In the periods from 2011 to 2014, some areas in the Duero River basin experienced increased surface runoff because of changes in land use and soil characteristics, such as clay texture and relief, which altered the infiltration capacity of the basin. This reduces the availability of water by the conversion of pastures to crops (Smith *et al*., 2016). These conversions lead to a drastic reduction in the water supply at local and national scales, changing the hydrologic cycle balance and increasing the impact of global warming (Rasmussen *et al*., 2014). Therefore, it is suggested that land cover/use changes should be characterized about anthropogenic activities in space and time to achieve conservation and the sustainable management of natural resources (Mawdsley, O'Malley, & Ojima, 2009).

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

Conclusions

The analysis of climatic variables in the Duero River basin showed a temperature increase of 0.8 °C and a decrease in precipitation of 90 mm from 1950 to 2010. The Duero River basin presents agro-climatic conditions for the development and growth of avocados. In this scenario, the pine-oak forest has been affected. Urban growth has affected only 1 % of the land area in the basin, but each year the impact of urban growth expands towards areas devoted to agriculture.

The results obtained from the SWAT model are satisfactory, including the R^2 value of 0.9 and the NS of 0.7, which indicate that it was a good model for simulating the behavior of the studied hydrological process. The conversion of land use and vegetation significantly affects the volume of surface runoff. Recovery of the vegetation in bare areas may serve to slow down the surface runoff, allowing infiltration and the reduction of water erosion.

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

Appendix 1. Summary of SWAT model parameters

Parameter	Description	Value
SOL_BD	Soil bulk density (g cm^{-3})	0.68-1.29
SOL_CBN	Soil organic carbon content (%)	0.53-11.00
SOL_K	Soil saturation conductivity (mm hr-1)	0.29-13.21
SOL_ALB	Soil albedo	0.01-0.42
CN2	Runoff curve number of moisture condition II	62-87
ESCO	Soil evaporation compensation factor	0.20
EPCO	Plant uptake compensation factor	1.00

Tecnología y ciencias del agua, ISSN 2007-2422, 13(1), 427-469. DOI: 10.24850/j-tyca-2022-01-10

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